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WADC TECHNICAL REPORT 54-83
Part 3

EXPERIMENTAL MAGNESIUM ALLOYS

Part 3 Thermal and Electrical Properties of Magnesium Base Alloys.

Edited by

H. A. Johnson, 1st Lt., USAF

Materials Laboratory

JUNE 1954

WRIGHT AIR DEVELOPMENT CENTER

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June 1954

Materials Laboratory Contract
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Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by The Dow Chemical Company under USAF Contract No. AF(600)19147. The contract was initiated under Research and Development Order No. R615-15 BA, "New Experimental Alloys by the Powder Metallurgy Process", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Lt H. A. Johnson acting as project engineer.

ABSTRACT

The effect of crystal orientation on the electrical resistivity of high-purity magnesium was determined. The results, at 24C, may be represented by the equation:

$$\rho(\phi) = 4.60 - 0.75 \cos^2 \phi,$$

where ϕ is the angle between the hexagonal axis and the direction of current flow.

The effect of temperature on the electrical resistivity for varying orientations was investigated, with temperature coefficients of .00390 and .00408/C obtained perpendicular and parallel to the hexagonal axis respectively for the temperature range of 24 to 200°C.

Extruded high-purity magnesium and ZK60A-T5 alloy were stressed in tension to various levels and the effect of this pre-stressing operation on the electrical resistivity recorded. There was no significant change in electrical resistivity at the levels investigated for either alloy.

Apparatus for the measurement of thermal conductivity, electrical conductivity and linear thermal expansion have been purchased or designed but are still in either the construction or calibration stage.

The advantages and disadvantages of electric resistance strain gages as a method of measuring the coefficient of linear thermal expansion are discussed.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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INTRODUCTION

This is part three of the Final Report on Contract Number AF(600)-19147 sponsored by the Materials Laboratory, Directorate of Research, W.A.D.C., covering the period July 1 - December 31, 1953 and pertaining to the determination of the physical properties of magnesium and magnesium alloys.

During this period the major effort has been toward the establishment of techniques and equipment for the measurement of physical properties of wrought magnesium alloys with immediate interest in the thermal expansion, thermal conductivity and electrical conductivity.

Several fundamental studies have been initiated in conjunction with the general physical property measurements in order to give a better understanding of the behavior of magnesium alloys. These are listed below:

1. The effect of crystal orientation on the electrical resistivity of high-purity magnesium.
2. The effect of temperature on the electrical resistivity of high-purity magnesium and magnesium alloys.
3. The relationship between thermal and electrical conductivities for magnesium alloys.
4. The effect of prestressing on the electrical conductivity and coefficient of linear thermal expansion of magnesium alloys.

SUMMARY OF EXPERIMENTAL RESULTS

1. The electrical resistivity of high-purity magnesium single crystals is linearly related to the square of the cosine of the angle between the hexagonal axis and the direction of current flow. At 24C the electrical resistivity is 4.60×10^{-6} ohms/cm^3 measured perpendicular to the hexagonal axis and 3.85×10^{-6} ohms/cm^3

measured parallel to the hexagonal axis.

2. The temperature coefficients of resistivity for high-purity magnesium measured perpendicular and parallel to the hexagonal axis are 0.00390 and 0.00408/C respectively for the temperature range from 24 to 200C.

3. Electric resistance strain gages are adequate for the measurement of thermal expansion coefficients at room temperatures. Values for the coefficient of thermal expansion for high-purity magnesium, EK30A-T6, ZK60A-T5 and HK31-T6 are given in Table 4.

4. Tensile prestressing of ZK60A alloy and high-purity magnesium had no apparent significant effect on electrical conductivity in the ranges of stress examined.

5. The electrical and thermal properties of EK30A, EK41A, ZK60A and pure magnesium are given in Table 5.

6. A Bollenrath commercial dilatometer for measuring the coefficient of linear thermal expansion is in the process of calibration.

7. Equipment for the measurement of thermal and electrical conductivity at elevated temperatures is still in the process of construction and calibration.

CONCLUSIONS

1. The electrical resistivity of high-purity magnesium single crystals is dependent on the crystal orientation. At 24C the relationship is represented by the equation $\rho(\phi) = 4.60 - 0.75 \cos^2 \phi$ where ϕ is the angle between the hexagonal axis and the direction of current flow.

2. Magnesium shows rotational symmetry about the hexagonal axis with respect to electrical resistivity.

3. Cast magnesium shows a random orientation of crystal growth.

4. The effect of grain size on electrical resistivity is negligible.

5. Electrical resistivity allows a rapid determination of crystal orientation in magnesium single crystals.

6. The temperature coefficient of resistivity varies with orientation in magnesium single crystals, varying from 0.00390/C perpendicular to the hexagonal axis to 0.00408/C parallel to the axis.

7. Although electric resistance strain gages are adequate for room temperature determinations of the coefficient of linear thermal expansion, the necessity for using selected gages and the time-consuming operations required make a commercial type dilatometer more feasible.

8. Within the ranges of 12,000 to 21,000 psi. for ZK60A alloy and 2,000 to 5,500 psi. for high-purity magnesium, prestressing in tension has no effect on electrical conductivity.

RECOMMENDATIONS

1. The effect of prestressing in compression on the electrical conductivity of high-purity magnesium and ZK60A alloy should be observed because of the different mods of deformation operative in compression.

2. Upon calibration of the dilatometric equipment similar observations should be made of the effect of prestressing on the coefficient of linear thermal expansion.

3. A very careful investigation should be made of the change in electrical resistivity with temperature for those single crystals with axes nearly parallel or perpendicular to the hexagonal axis. This should detect the sharp increase in c/a ratio at a certain threshold temperature peculiar to the particular alloy under investigation as shown by Busk[1].

THE EFFECT OF CRYSTAL ORIENTATION ON THE ELECTRICAL RESISTIVITY OF HIGH-PURITY MAGNESIUM.

The effect of crystal orientation on the electrical resistivity of high-purity magnesium was determined for three primary reasons: (1) in order to verify the existing data in the literature, (2) to obtain a rapid method of determining the amount of preferred orientation in wrought magnesium alloys and (3) to attempt to further the present understanding of electrical conductivity theory in hexagonal metals.

Schmid[2] and Goens and Schmid[3] investigated the effect of orientation on electrical resistivity, finding the specific electrical conductivity of magnesium single crystals to be linearly related to the square of the cosine of the angle between the hexagonal axis and the direction of current flow. According to Schmid, the resistivity at 18C is 4.54×10^{-6} ohms/cm^3 perpendicular to the hexagonal axis, and 3.77×10^{-6} ohms/cm^3 parallel thereto, and their respective temperature coefficients are 0.00416 and 0.00427/C. The purity of his magnesium was reported as approximately 99.95%.

Bridgman[4] has obtained several of the directional properties for high-purity magnesium, including the electrical resistivity. He, too, found that magnesium did not satisfy the expectations of a close-packed hexagonal metal, observing that the resistance not only varied materially with direction but, unlike almost all other non-cubic metals, the resistance was greater perpendicular to the hexagonal axis. At 22.5C, Bridgman records the specific resistance as 3.89×10^{-6} ohms/cm^3 parallel to the axis and 4.60×10^{-6} perpendicular to it. The temperature coefficient of resistance at atmospheric pressure between 0C and 100C was 0.00523 and 0.00428/C respectively.

In an effort to obtain the highest purity material available, the magnesium used in this investigation was submitted to four sublimations in vacuo and cast under argon with a resultant purity of approximately 99.98%. Spectrographic analyses for this material are given in

Table 1. The above purity is by difference.

Twenty-five magnesium single crystals were grown from the melt in a gradient furnace using a temperature differential to promote nucleation at the base of the crystal. These crystals were in the form of one-half inch rod, approximately seven inches in length. The high-purity material was first extruded in the form of one-half inch rods and then inserted in a graphite crucible for subsequent melting. The crucibles used contained three openings for the melting stock enabling three single crystals to be grown in an individual run. The extruded rod was rapidly melted under argon in a sealed furnace and the temperature raised to 710C, held for a short time and then allowed to cool at the controlled rate of approximately 5C per hour. A yield of about 80% was obtained in the production of high-purity magnesium single crystals using this method.

The orientations of the twenty-five single crystals were determined using the Laue back-reflection technique and were the average of two determinations on each crystal at 90° rotation to each other. These invariably checked within 1° when plotted stereographically. A small amount of lineage was observed (as indicated by a separation of the Laue spots) in a few of the specimens; however, close observations of these crystals in subsequent physical property measurements disclosed no anomalies. The basic hexagonal triangle for each crystal was plotted, enabling a statistical calculation of the probability of growing a magnesium single crystal of a definite orientation. Table 2 shows the expected and observed distributions for twenty-five single crystals as a function of the angle between the specimen axis and the hexagonal plane. The expected frequencies are based on the area of 10° segments of a 30° sector of a hemisphere on the reference sphere, and not on the areas of the stereographic net, since these areas are not proportional in any perspective projection. Figure 1 shows the relation between the expected and observed frequency of orientation. From the results obtained it is observed that the orientation of a magnesium single crystal formed from the melt by the described method is purely a random

function of the area of the basic hexagonal triangle and shows no preferred growth orientation. The "goodness of fit" of the observed curve with the expected curve was examined by the "chi-square" test. The χ^2 value of 4.56, as given in Table 2, is associated with a probability range of 0.5 - 0.75 (depending on the number of degrees of freedom chosen) that χ^2 will be at least as great or greater than the value obtained. This indicates that the hypothesis set forth should be accepted; i.e., that the growth of a single crystal of magnesium by the method described gives a random orientation of the specimen axis with respect to the hexagonal pole in accordance with the area of the spherical triangle on the reference sphere bounded by the hexagonal pole, the [210] and the [100] directions.

After determination of orientations, the crystals were etched to reduce contact resistance in the electrical measurements. A double-Kelvin bridge was used in conjunction with a high-sensitivity D'Arsonval type galvanometer. Previous measurements had been made on an electronic type galvanometer which led to excessive scatter in the resulting resistivities. From four to six measurements were taken on each bar and the average of these readings was used as the resistance of the bar. The readings were taken in a constant temperature room in which the temperature was held to ± 1F for the duration of measurement.

The results of this investigation are shown in Figures 2-7 inclusive. Figures 2 and 3 give the electrical resistivity, ρ, and conductivity, K, respectively at 24C, plotted against cosine^2 ϕ where ϕ is the angle between the hexagonal axis and the direction of current flow. These plots show very little scatter with standard deviations, σ, of ± 0.01 x 10^{-6} ohms/cm^3 for the resistivity and ± 0.07 x 10^4 mhos/cm^3 for conductivity. The resistivities ⊥ and // to the hexagonal axis for this investigation, along with those of Schmid[2][3] and Bridgman[4], extrapolated to the constant temperature of 18C, are given on the next page.

	$\rho_\perp$ (10^{-6} ohms/cm^3)	$\rho_\parallel$ (10^{-6} ohms/cm^3)
This Study:	4.48 ± .01	3.74 ± .01
Schmid[2][3]	4.54	3.77
Bridgman[4]	4.50	3.80

From these data it can be deduced that the magnesium used in this investigation was of sufficiently high-purity to yield a real difference from previous investigations.

Several attempts were made to find some correlation between resistivity and direction in the basal plane. It was felt that if any effects were observed it should be for angles of ϕ between 45 and 90°; however, the scatter in the data was quite small and further refinement was not possible by considering the azimuthal rotation in the basal plane. Any azimuthal effects around the C axis, of course, would be repetitive for every 60° rotation. It was not unexpected to find no directional effects on resistivity in the basal plane since other investigators[2][3][5] report rotational symmetry around the hexagonal axis. Orientation, then, with respect to electrical resistivity is sufficiently defined by the angle ϕ between the hexagonal axis and the direction of current flow. Since the extreme resistivity values are observed parallel and perpendicular to the hexagonal axis, the resistivity at any particular intermediate angle ϕ is given by the following expression:

$$\rho(\phi) = \rho_\perp \sin^2\phi + \rho_\parallel \cos^2\phi$$

Substituting $\sin^2\phi = 1-\cos^2\phi$ we obtain:

$$\rho(\phi) = \rho_\perp + (\rho_\parallel - \rho_\perp) \cos^2\phi$$

For high-purity magnesium at 24C this becomes:

$$\rho(\phi) = 4.60-0.75 \cos^2\phi$$

A possible source of error was found in the type of specimen clamps used. The sample holder employed spring clamps which undoubtedly incited some twinning in the specimens. However, since subsequent readings on the bar showed no change, it is safe to assume that any twinning which may have occurred was extremely localized in character and caused very minor changes in resistance which were beyond the sensitivity of the bridge.

THE EFFECT OF TEMPERATURE ON THE ELECTRICAL RESISTIVITY OF HIGH-PURITY MAGNESIUM.

A continuation of the previous work was the determination of the temperature coefficients of resistance for magnesium single crystals of various orientations. Ten crystals were chosen, having $\cos^2\phi$ values ranging from .001 to .990, enabling complete coverage of the angular relationships between the hexagonal axis and direction of current flow. A constant temperature bath was obtained using peanut oil as the heat exchange medium. In this investigation an upper limit of 200C was imposed because of the construction material of the specimen holder. Once more, a double-Kelvin bridge was employed along with a D'Arsonval galvanometer as the resistance measuring instrument.

The results of these measurements are shown in Figures 4, 5 and 6. Figure 4 is a plot of the electrical resistivity versus temperature on a scale of sufficient size to register all the data points. Figure 5 is a greatly expanded plot of Figure 4 to enable accurate extrapolation for the determination of the OC intercept on the vertical axis. The R_o values are obtained from the intercepts in Figure 5 and the ratio of the slope to R_o gives α, the coefficient of resistivity. The resistivity then, at any temperature in question between OC and 200C is given by the relation: $R_T = R_o (1 + \alpha T)$. The values for R_o and α obtained in this study are given in Table 3. In Figures 4 and 5 there were several duplications of orientation so that only six curves are shown. The results show a small, approximately linear, change in α with orientation, varying from 0.00390/C ($\sigma = \pm 0.00003$°C) perpendicular to the hexagonal axis to 0.00408/C parallel thereto. These values

compare very favorably with Schmid's results, being on the order of 0.0002/C lower but similar in slope. Bridgman's values are considerably higher than those of this study and of Schmid which tend to favor the coefficients obtained in the latter two studies. These values are recorded for comparison in Table 3.

Figure 6 is a plot of electrical conductivity versus temperature for (1) high-purity magnesium single crystal #4 having a $\cos^2\phi$ value of .206 and an angle ϕ of 63° and for (2) fine-grained polycrystalline magnesium die castings as given by Grube and co-workers[6][7][8][9][10]. Figure 7 (after Betterton[11]) shows the conductivity of high-purity magnesium as a function of grain size. The values in Figure 7 were obtained using a Biddle Ohmmeter, thus accounting for the excessive scatter observed as compared to the results obtained utilizing a Kelvin Bridge. Betterton gives the standard deviation of the Biddle instrument as 1.6 times that of the Kelvin instrument. However, statistical analysis of the data in Figure 7 showed no change in conductivity with decreasing grain size. Literature discussions have suggested that the effect of grain size on electrical resistivity is negligible. Figures 6 and 7, then, give further corroboration to this fact. The near-coincidence of the two curves in Figure 6 gives additional experimental verification of two observed phenomena; first, that grain size has little or no effect on the electrical resistivity of high-purity magnesium and, second, that magnesium tends to grow from the melt with a random orientation. Crystal Number 4 has an orientation of $\phi = 63°$ which is very close to the median or center of gravity value. This value is $\phi = 60°$ if the only consideration is of the area of the spherical triangle on the reference sphere; that is, the point where it is equally probable for the specimen axis to fall above or below this orientation with reference to the hexagonal pole. More correctly, however, it should be stated that in a random polycrystalline aggregate there is an average resistivity, this value being based on the equation obtained from Figure 2. This average resistivity value occurs where $\cos^2\phi = .666$ or $\phi = 35°$. In either event, the curve for crystal number 4 would be displaced upward a small amount. The small discrepancy between the two curves in Figure 6 is readily accounted for by reference to the difference in resistivities of die-cast

and sand-cast metals. Beck[12] shows die castings average roughly $0.40 - 0.80 \times 10^4$ mhos/cm^3 less than sand-cast material because of porosity and density considerations. Correcting for this fact and for the orientation deviation from the average value would bring the curves into coincidence.

An investigation of the more favorably oriented crystals should be undertaken to try to observe with resistivity measurements the sharp change in the c/a ratio with temperature. Busk[1] observed this phenomenon in high-purity magnesium near 200C. In order to detect this, high sensitivity resistivity measurements must be made for every few degrees rise in temperature.

RELATIONSHIP BETWEEN THERMAL AND ELECTRICAL CONDUCTIVITY FOR MAGNESIUM ALLOYS.

Previous thermal conductivity determinations have been based on the conversion from electrical conductivity utilizing the Wiedemann-Franz-Lorenz relationship. Since the measurement of electrical resistance is a much more accurate measurement, entailing considerably fewer experimental difficulties, it is advantageous to use this relationship for thermal conductivity determinations.

Powell[13] has obtained a linear relationship between the thermal and electrical conductivities of eight magnesium alloys at temperatures of 50, 150 and 250C. He shows that these results can be represented by the equation:

$K = 0.526 \times 10^{-8} \sigma T + 0.027$ to within 3.5% where K is the thermal conductivity expressed in gram-calories per square cm. per second for 1 cm. thickness and 1C difference in temperature, σ is the electrical conductivity expressed in reciprocal ohms per cubic cm. and T is the absolute temperature. Powell has also made an analysis of all existing data for the conductivities of magnesium and magnesium alloys from which it is concluded that the equation $K = 0.516 \times 10^{-8} \sigma T + 0.022$ can be used to give an approximate value for the thermal conductivity of such metals.

Bungardt and Kallenbach[14] also have surveyed the range of validity and application of an expanded Wiedemann-Franz-Lorenz equation for magnesium and magnesium alloys, concluding that the results of all existing investigations may be expressed by the equation $K = 0.54 \times 10^{-8} \sigma T + 0.4 \times 10^{-4} T$. It is important to observe that at room temperature there is excellent agreement between Powell and Bungardt.

It is the purpose of this laboratory, then, to further the work in this field by attempting to obtain conclusively a relationship whereby the thermal conductivity of magnesium alloys may be determined with reasonable accuracy by the measurement of electrical conductivities.

A procedure has been adopted similar to that of Hogan and Sawyer[15] using a modified Forbes bar lateral-leakage method. This method has the advantage of simultaneous measurement of electrical and thermal conductivities at a nearly constant temperature; thus, the effect of the true internal structure on the resistivity can be observed at the temperature under consideration. This effect is missed in other methods having a large temperature gradient over the length of the specimen.

At the present date, the furnace is completed for these measurements and the instrumentation is in progress. It is expected that the apparatus will be ready for calibration in the near future.

THERMAL EXPANSION OF MAGNESIUM AND MAGNESIUM ALLOYS.

One of the most important physical properties in the determination of magnesium alloy applications is the coefficient of linear thermal expansion. A commercial dilatometer of the Bollenrath type has been obtained for the measurement of thermal dimensional changes of both new and established magnesium alloys. This instrument has just been received and calibration of the apparatus is now in progress.

A further interest in thermal expansion has been kindled by the published works of Rosenholtz and Smith[16][17][18]. These papers

relate changes in linear expansion to internal physical phenomena and, in turn, to useful mechanical properties. The authors found sharp discontinuities in the thermal expansion coefficient of prestressed materials and postulate these anomalies as being evidence of the true endurance limit, yield point or proportional limit depending on the type of prestressing operation. For example, a discontinuity of 18% in the expansion coefficient of magnesium was found when plotted against applied compressive stress. The stress at the point where the dip occurs was designated as the true yield point. A similar dip of the thermal expansion coefficient is observed at the true endurance limit when the prestressing operation is of the fatigue type. This so-called "Dilastrain" method of determining the endurance limit of materials may have considerable utility since the number of stress reversals necessary to determine the endurance limit by this method is on the order of only 100,000 cycles. A study has been initiated in our laboratories to ascertain the validity of these relations.

While awaiting delivery of the Bollenrath dilatometer, an investigation was started to determine the feasibility of using electrical resistance strain gages for measuring thermal expansion. Hidnert[19] at the National Bureau of Standards has used these successfully in measurements on glass, finding that with selected gages it is possible to attain an accuracy near 1% of the coefficient. A constant temperature bath was constructed and measurements made on several standard materials. Baldwin-Lima-Hamilton SR4 gages, type AD-7, were used in conjunction with a Baldwin-Lima-Hamilton SR4 strain indicator. The gages were mounted on the specimens (1/2" rod) with Duco cement as the adhesive and microcrystalline wax or Ten-X compound used as a waterproofing agent. Compensating gages were mounted on quartz in a similar manner. In many cases, faults in mounting technique or gage variation gave erroneous results. The method was encouraging, however, for room temperature measurements, but the cost and limitations of high temperature gages were prohibitive for general use.

Figure 8 shows the expansion versus temperature curve for extruded high-purity magnesium, annealed for one hour at 300C. This

curve is the result of measurements on five identical specimens and shows a straight line relationship with very little scatter. The departure from linearity observed at approximately 37C is the point where gage slippage first occurs due to the adhesion characteristics of the cement employed. From this curve it may be seen that electric resistance strain gages offer a reasonably accurate method of measuring the thermal expansion coefficient of metals at room temperatures. However, the method is time-consuming and heavily dependent on the individual gage characteristics and mounting techniques which tend to favor a more conventional type dilatometer at temperatures above 35C.

In addition to the values obtained for high-purity magnesium, the coefficients of linear thermal expansion for cast EK30A-T6, cast HK31-T6 and extruded ZK60A-T5 have been obtained by this method. These values are presented in Table 4.

THE EFFECT OF PRESTRESSING ON ELECTRICAL CONDUCTIVITY.

In an effort to verify the work of Rosenholtz and Smith[16][17][18] on the effect of prior strain history on the coefficient of linear thermal expansion, it was proposed that a similar survey be made on the electrical properties of magnesium. Rosenholtz and Smith suggest that other physical properties of the strained metal are affected in a manner similar to the coefficient of expansion. Since these workers have reported values on pure magnesium and ZK60A-T5 it was proposed that the same alloys be used in our work.

One billet each of ZK60A and sublimed, vacuum cast magnesium was extruded into 1/2" rod. Electrical conductivity measurements were made on 7" specimens cut from this material. The ZK60A alloy was then heat treated to the -T5 condition and the high-purity magnesium was annealed for two hours at 450F. Upon completion of the heat treatment the electrical conductivities of the specimens were again measured.

Sixteen specimens of each alloy were then stressed in tension over a range which was thought to include the proportional limit of the

material. The ZK60A alloy was stressed from 12,000 to 20,000 psi. in increments of 500 psi. The pure magnesium specimens were stressed in duplicate from 2,000 to 5,500 psi. in increments of 500 psi.

Figures 9 and 10 show the electrical conductivity plotted as a function of applied stress for these magnesium alloys. The dashed lines in these graphs give the upper and lower limits of scatter, being plus or minus three times the root-mean-square deviation ($\pm 3\sigma$). It is observed that in none of the cases is a 3σ limit exceeded with the resultant conclusion that in the alloys investigated prestressing in tension has no effect on the electrical conductivity over the range shown. In Figure 10, the change in conductivity that occurs upon stressing in tension is plotted against stress and once more no datum point exceeds $\pm 3\sigma$. There is an overall change in the mean ($\bar{X}$) of these values (22.13 to 22.09 . 10^4 mhos/cm^3) but this is insignificant when the RMS deviation of 0.08 x 10^4 mhos/cm^3 is considered.

Similar measurements had been made originally with an electronic galvanometer obtaining the same results as above on specimens having identical treatment. The present readings were made using a Leeds and Northrup high sensitivity galvanometer in conjunction with a double-Kelvin bridge.

This work will be continued by broadening the limits for the tensile stressing in order to be certain that the entire range is well-covered. Specimens submitted to compression tests will also be investigated because of the different mode of deformation operative.

GENERAL PHYSICAL PROPERTIES.

During the course of these investigations several of the desired physical properties for wrought and cast magnesium alloys have been obtained. At this stage, these alloys have been from a random selection rather than an organized survey. These values are listed in Table 5. The thermal conductivity values listed have been obtained by theoretical calculations from the Wiedemann-Franz-Lorenz relation and

not by direct experimental measurements. The value in each case is an average of the value obtained from the Powell and Bungardt equations. In most cases, these two values were identical.

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TABLE 1

SPECTROGRAPHIC ANALYSIS OF SUBLIMED MAGNESIUM

% C = 0.0036	% Mn = 0.0002	% Ca = 0.0010
% Fe = 0.0005	% Si = <.001	% K = 0.0019
% Pb = <.0005	% Cu = <.0001	% Na = 0.0019
% Zn = <.01	% Ni = <.0003	% Sr = <.0001
% Al = <.0001	% Sn = <.001	% B = <.0001
		% H = 0.0004

TABLE 2

DISTRIBUTION OF ORIENTATION RELATIONSHIPS IN 25 MAGNESIUM SINGLE CRYSTALS

< Between Hex. Plane and Specimen Axis	O Observed Frequency	% Area in 30° Sector	E Expected Frequency	(O-E)	$(O-E)^2$	$\frac{(O-E)^2}{E}$
0-10	4	17.4	4.35	0.35	0.132	0.030
11-20	6	16.8	4.20	1.80	3.240	0.765
21-30	5	15.8	3.95	1.05	1.104	0.280
31-40	4	14.3	3.56	0.44	0.194	0.052
41-50	2	12.3	3.08	1.08	1.170	0.379
51-60	1	10.0	2.50	1.50	2.250	0.900
61-70	2	7.4	1.85	0.15	0.023	0.011
71-80	0	4.5	1.13	1.13	1.280	1.130
81-90	1	1.5	0.38	0.62	0.385	1.012

$$\sum \frac{(O-E)^2}{E} = 4.559 = \chi^2$$

TABLE 3

TEMPERATURE COEFFICIENTS OF RESISTIVITY FROM 24C TO 200C FOR HIGH-PURITY MAGNESIUM SINGLE CRYSTALS OF VARIOUS ORIENTATIONS

Crystal No.	ϕ	$\cos^2\phi$	α, Temperature Coefficient of Resistivity, (per C)
1	48	.448	.00397
3	87	.003	.00390
4	63	.206	.00392
6	24	.835	.00400
7	50	.413	.00397
9	34	.687	.00398
10	23	.848	.00400
22	6	.990	.00408
23	62	.220	.00392
24	88	.001	.00390

	$\alpha_\perp$ (per C)	$\alpha_\parallel$ (per C)
This Study	0.00390	0.00408
Schmid	0.00416	0.00427
Bridgman	0.00428	0.00523

TABLE 4

THERMAL EXPANSION COEFFICIENTS OF MAGNESIUM ALLOYS

Alloy	Fabrication	Heat Treatment	Temp. Range	$\alpha \times 10^{-6}$ (in/in/C)
High Purity Mg	Extruded	1 hour at 300C	20-35C	25.2 ± .3
HK31A	Cast	-T6	20-35C	25.9 ± .5
EK30A	Cast	-T6 { 16 hrs-1050F, 16 hrs-400F	20-35C	26.0 ± .5
ZK60A	Extruded	-T5 24 hrs-300F	20-35C	24.6 ± .5

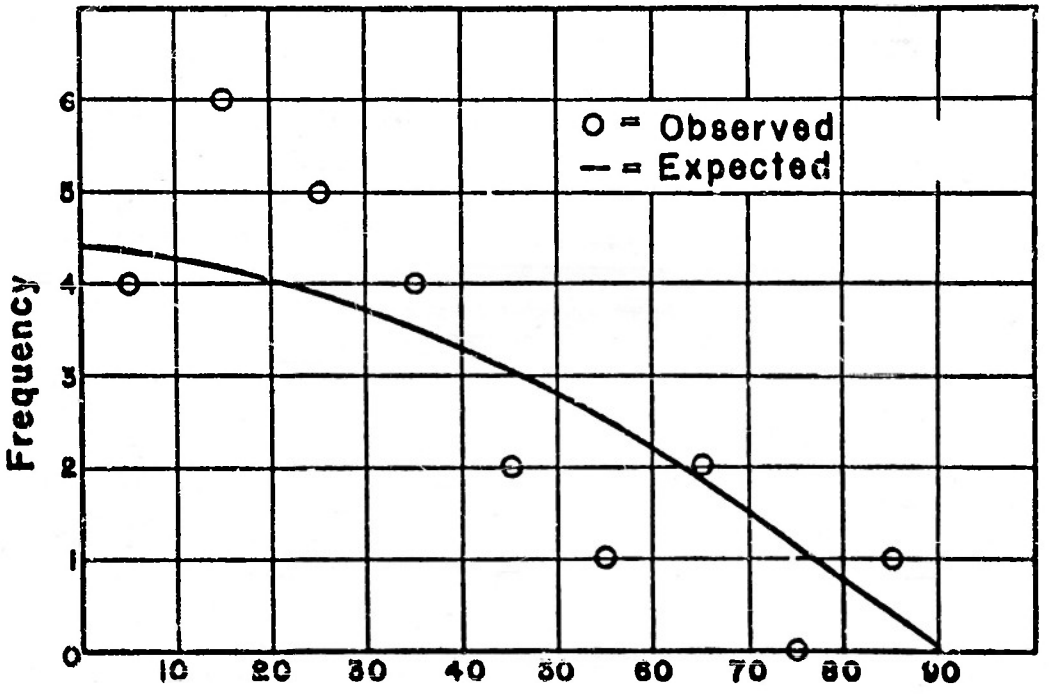
TABLE 5

ELECTRICAL AND THERMAL PROPERTIES OF MAGNESIUM ALLOYS

Alloy	Fabrication	Heat Treatment	Electrical Conductivity at 20C (10^4 Mhos/cm)[1]	Thermal Conductivity at 20C (c.g.s. Units)[2]	Electrical Conductivity % IACS[3]
High Purity Magnesium	Extruded	---	21.95	.361	37.8
High Purity Magnesium	Extruded	2 hours at 400F	22.40	.370	38.6
ZK60A	Extruded	---	16.77	.280	28.9
ZK60A	Extruded	-T5 24 hrs-300F	17.65	.294	30.4
EK30A	Extruded	---	14.35	.240	24.7
EK41A	Extruded	---	14.25	.238	24.6
EK30A	Cast	-T6	14.80	.250	25.2
EK41A	Cast	-T6	13.70	.230	23.6
EK41A	Cast	-T5	15.22	.252	26.2

1. RMS deviation ($\pm\sigma$) = $\pm$ 0.08
2. Quoted by Powell[13] as $\pm$ 5% (maximum deviation)
3. RMS deviation ($\pm\sigma$) = $\sim \pm$ .15%

FIG. 1 - Orientation Angle versus Frequency of Occurrence for 25 Magnesium Single Crystals.



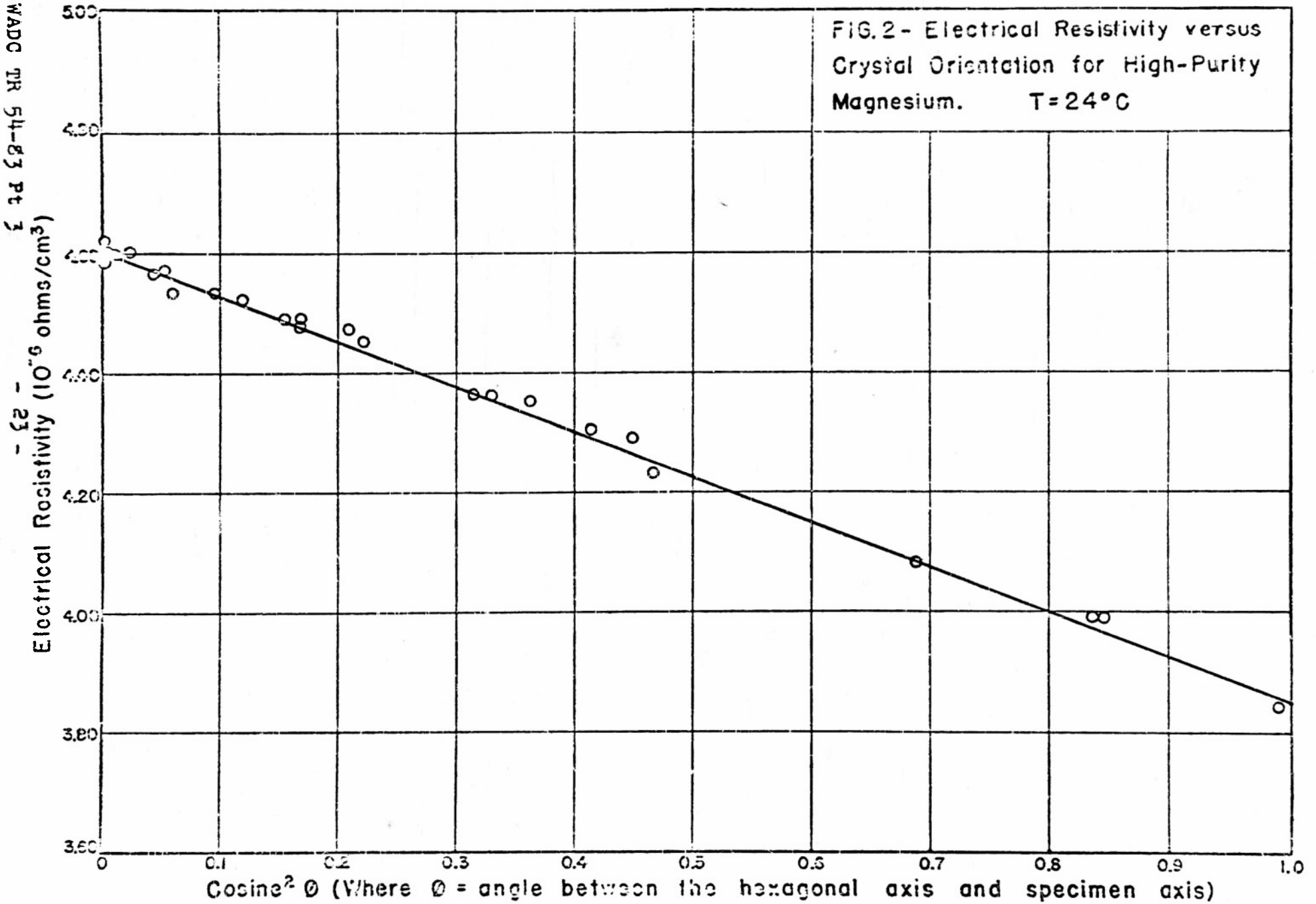


FIG. 2 - Electrical Resistivity versus Crystal Orientation for High-Purity Magnesium. T = 24°C
Electrical Resistivity (10^{-6} ohms/cm³)
5.00
4.80
4.60
4.40
4.20
4.00
3.80
3.60
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Cosine² Ø (Where Ø = angle between the hexagonal axis and specimen axis)

FIG. 5 - Electrical Conductivity versus Crystal Orientation for High-Purity Mg.

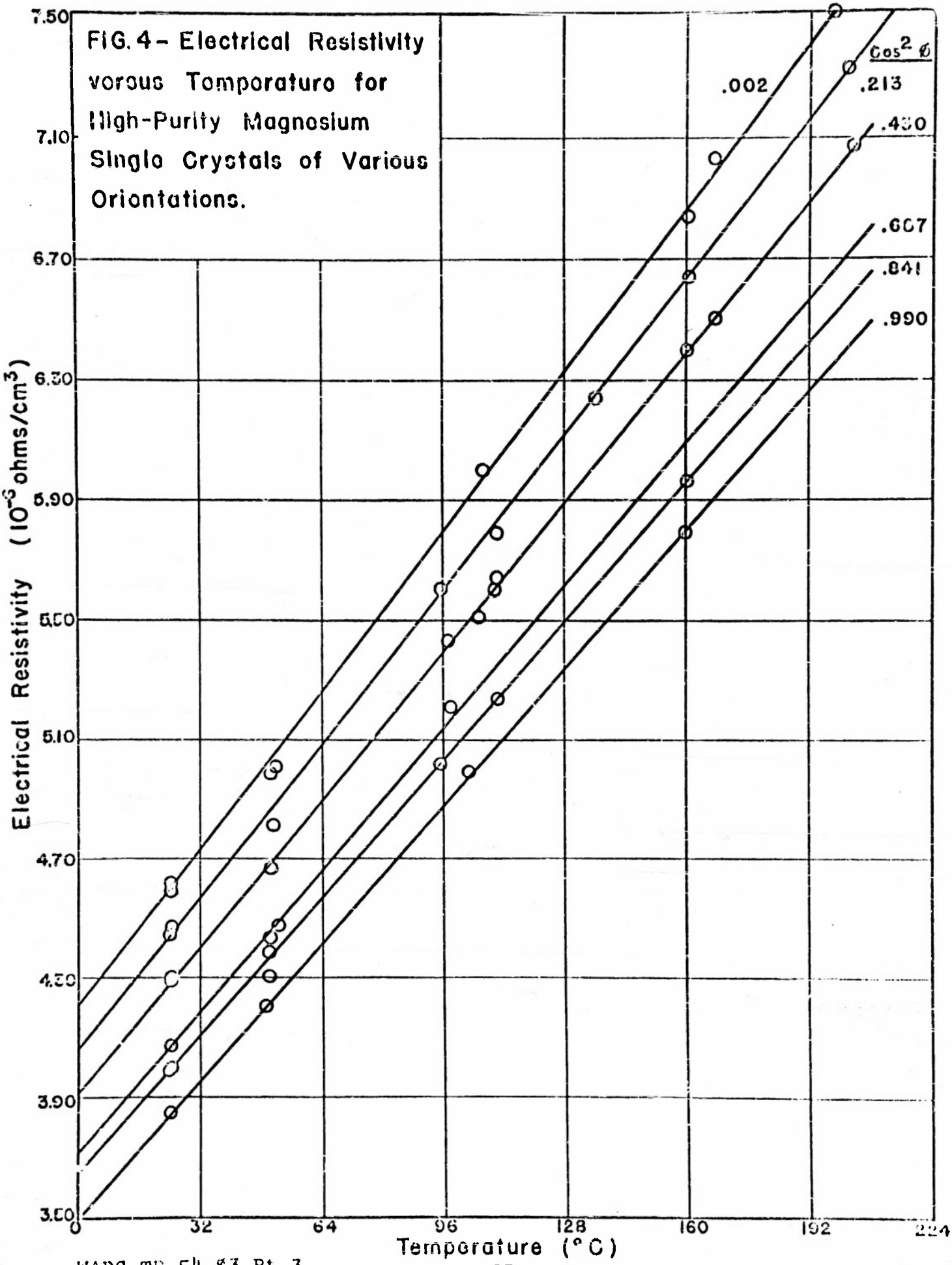


FIG. 4 - Electrical Resistivity versus Temperature for High-Purity Magnesium Single Crystals of Various Orientations.
Cos² ϕ
.002
.213
.430
.607
.841
.990
Electrical Resistivity (10⁻³ ohms/cm³)
7.50
7.10
6.70
6.30
5.90
5.50
5.10
4.70
4.30
3.90
3.50
0
32
64
96
128
160
192
224
Temperature (°C)

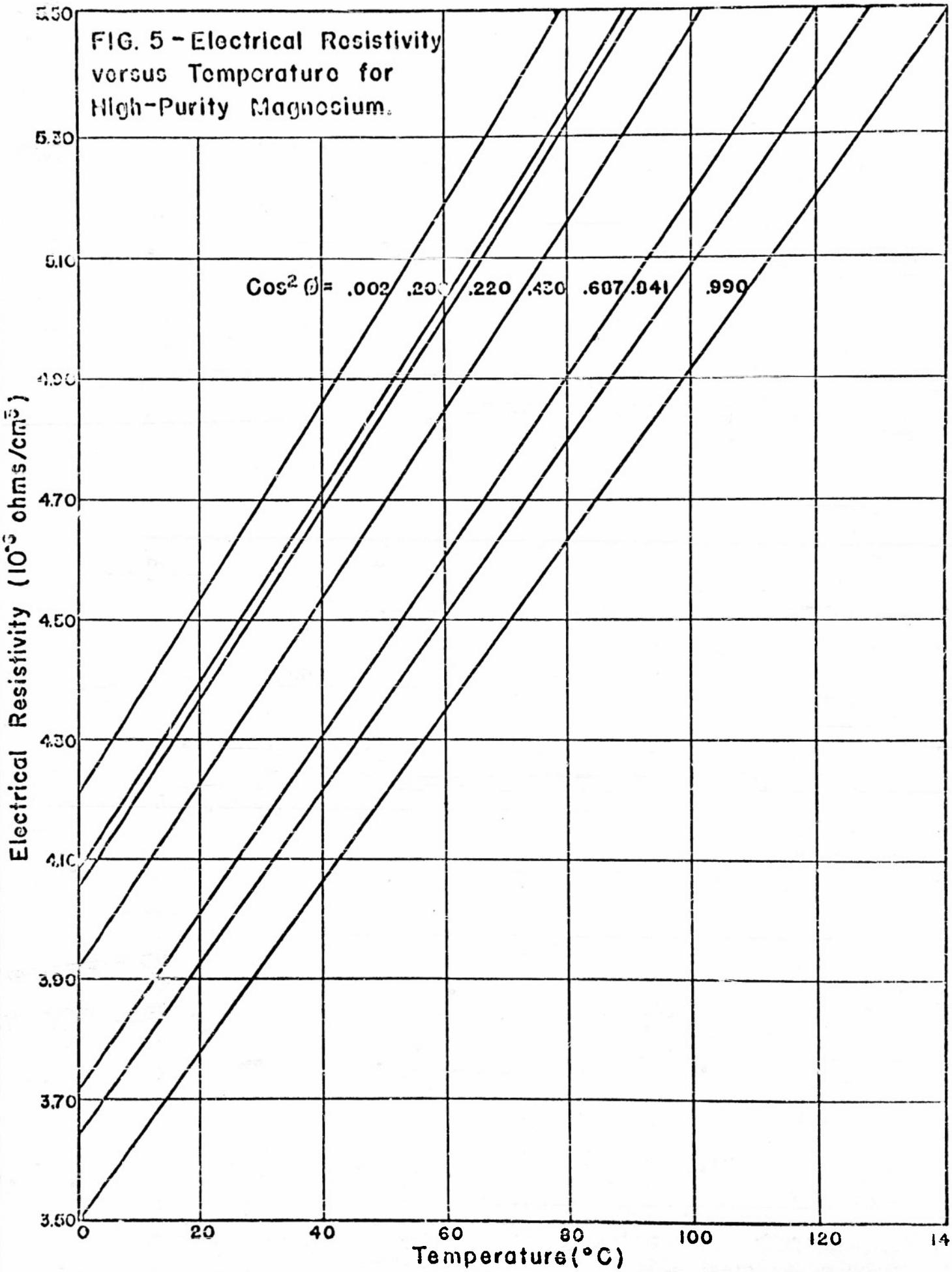


FIG. 5 - Electrical Resistivity versus Temperature for High-Purity Magnesium.
Cos² Ø = .002 .220 .430 .607 .841 .990
Electrical Resistivity (10⁻⁶ ohms/cm³)
5.50
5.30
5.10
4.90
4.70
4.50
4.30
4.10
3.90
3.70
3.50
0
20
40
60
80
100
120
140
Temperature (°C)

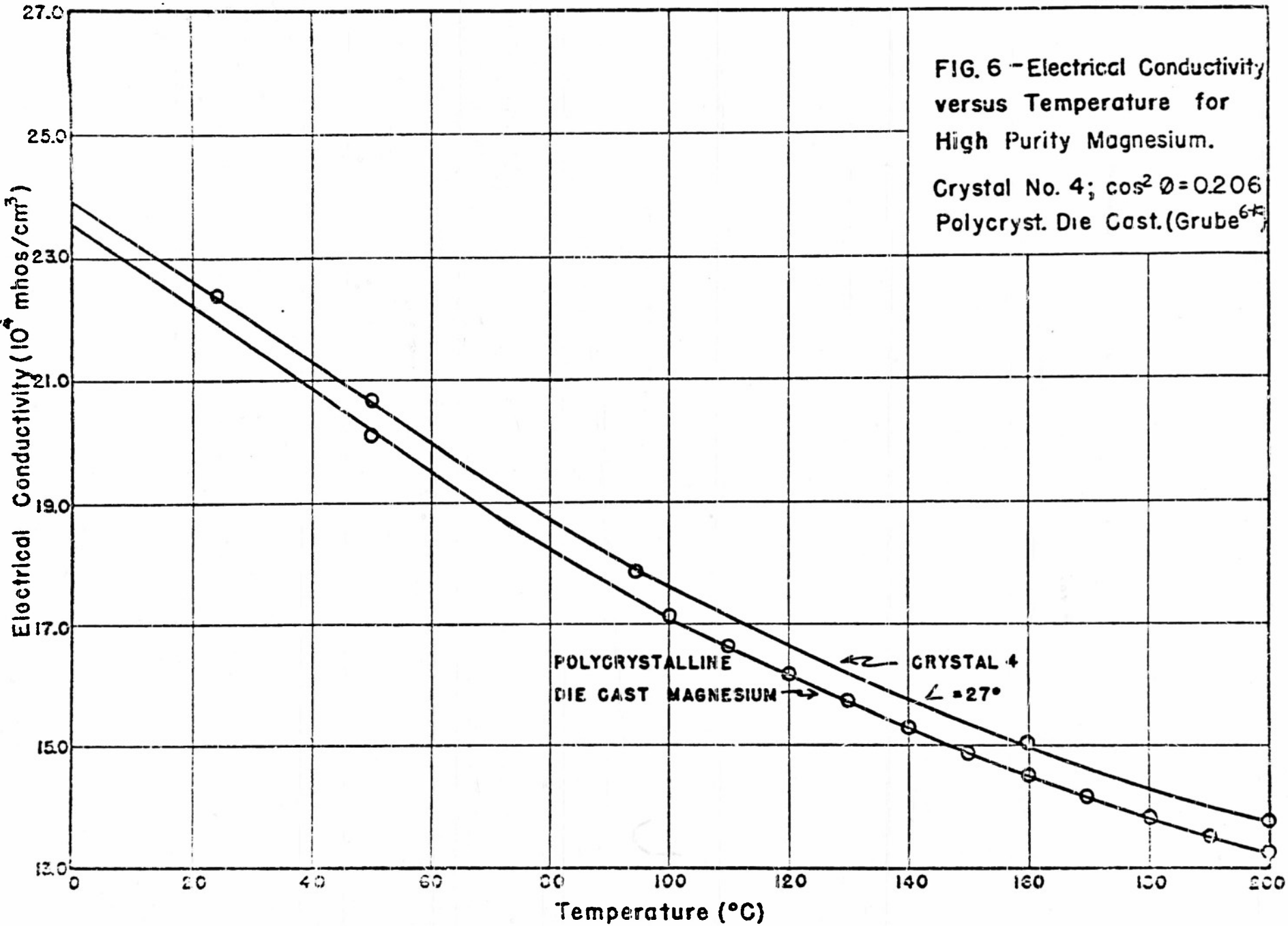


FIG. 6 - Electrical Conductivity versus Temperature for High Purity Magnesium.

Crystal No. 4; $\cos^2 \emptyset = 0.206$

Polycryst. Die Cast. (Grube[6])

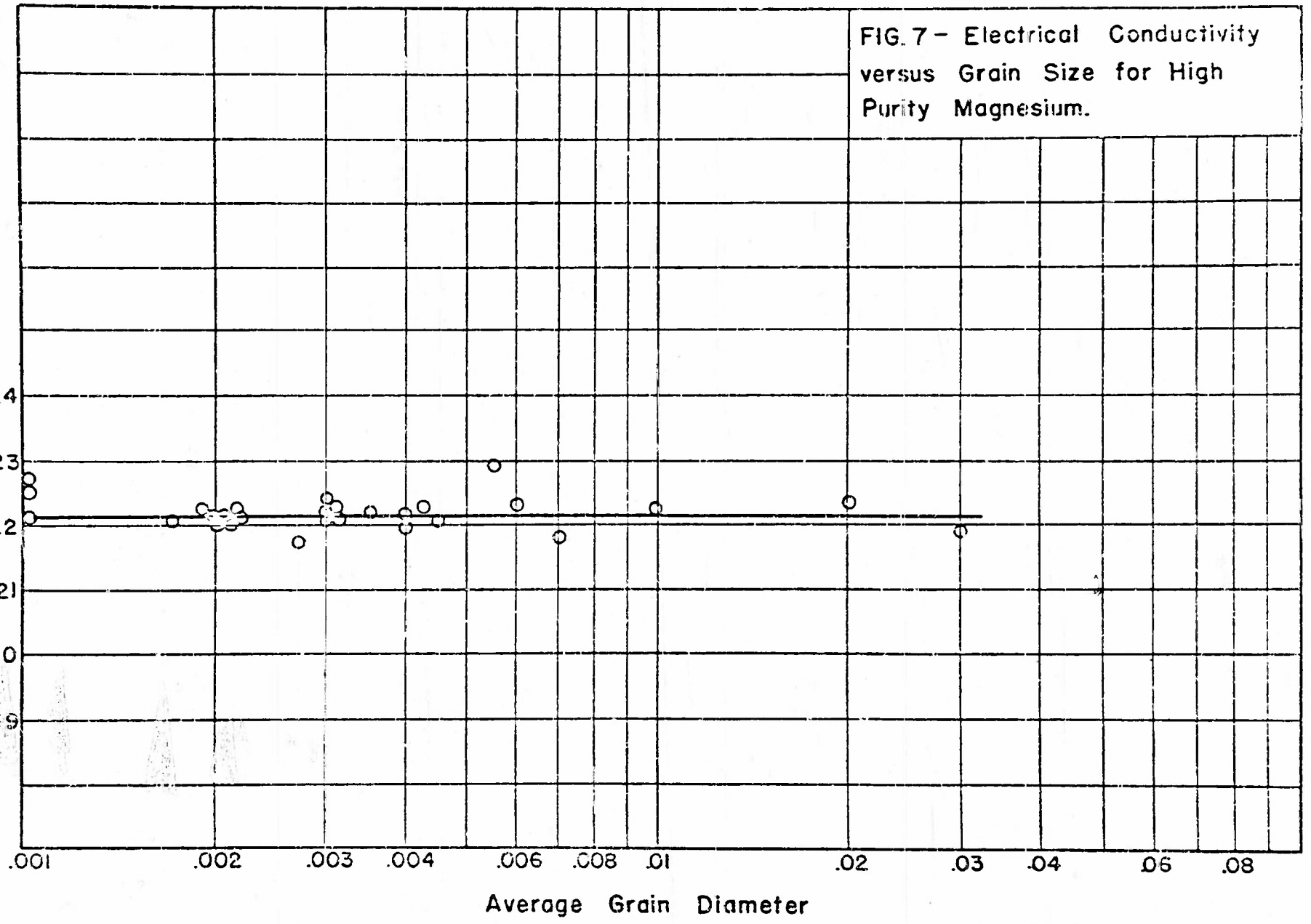


FIG. 7 – Electrical Conductivity versus Grain Size for High Purity Magnesium.

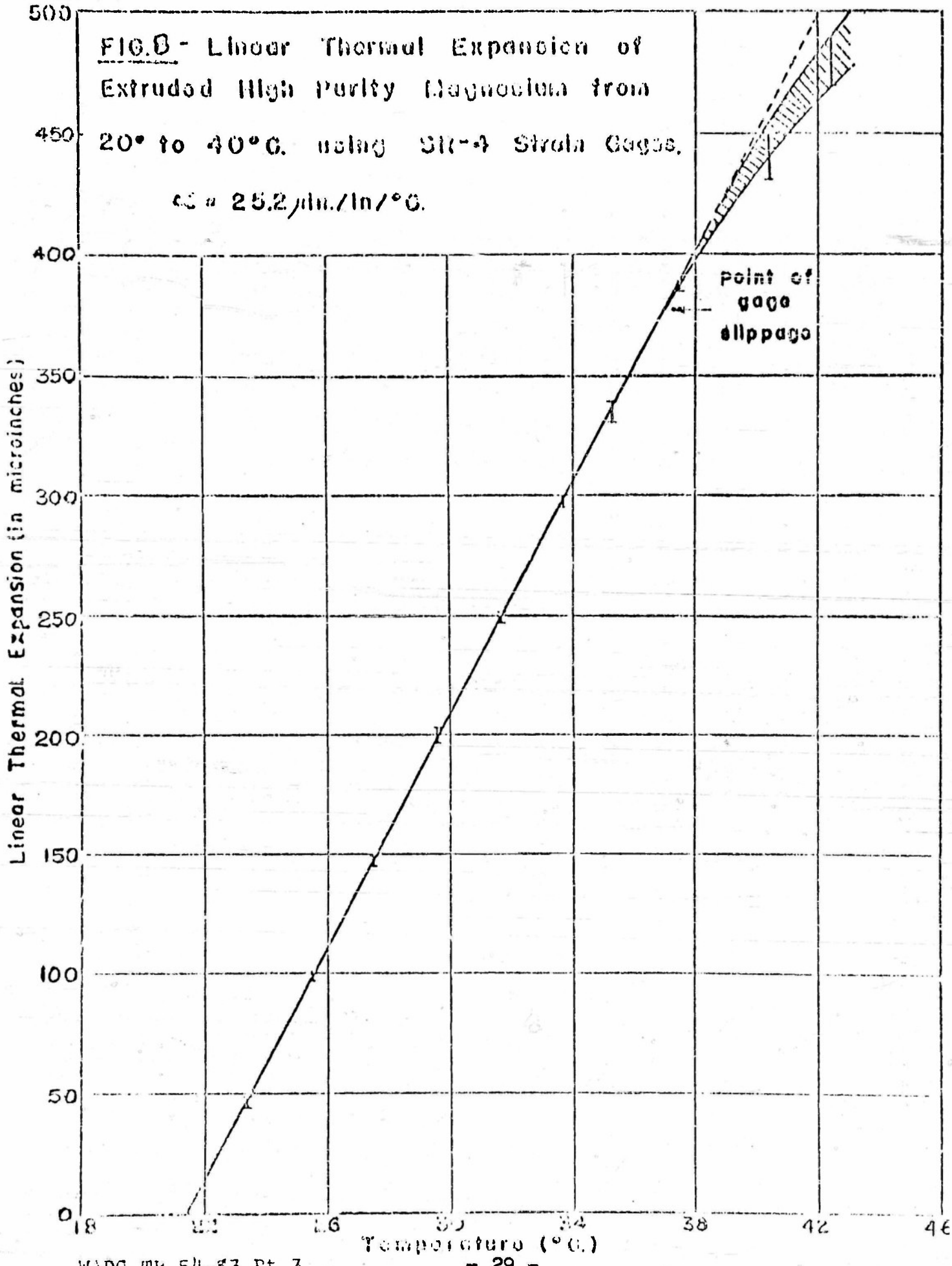


FIG.8 - Linear Thermal Expansion of Extruded High Purity Magnesium from 20° to 40°C. using SR-4 Strain Gages.
α = 25.2 μin./in/°C.
Point of gage slippage
Linear Thermal Expansion (in microinches)
Temperature (°C.)
500
450
400
350
300
250
200
150
100
50
0
18
22
26
30
34
38
42
46

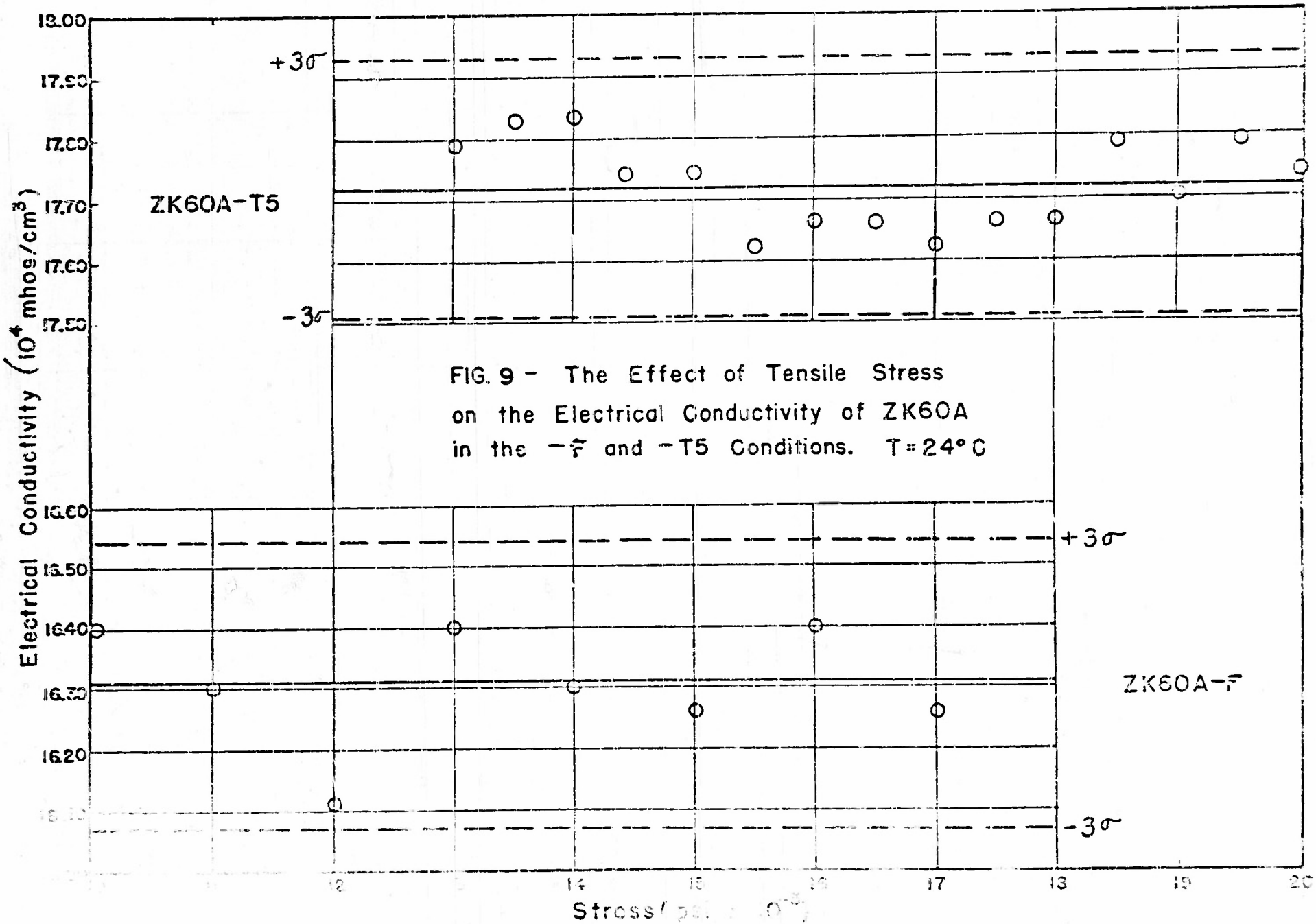


FIG. 9 - The Effect of Tensile Stress on the Electrical Conductivity of ZK60A in the -F and -T5 Conditions. T = 24° C

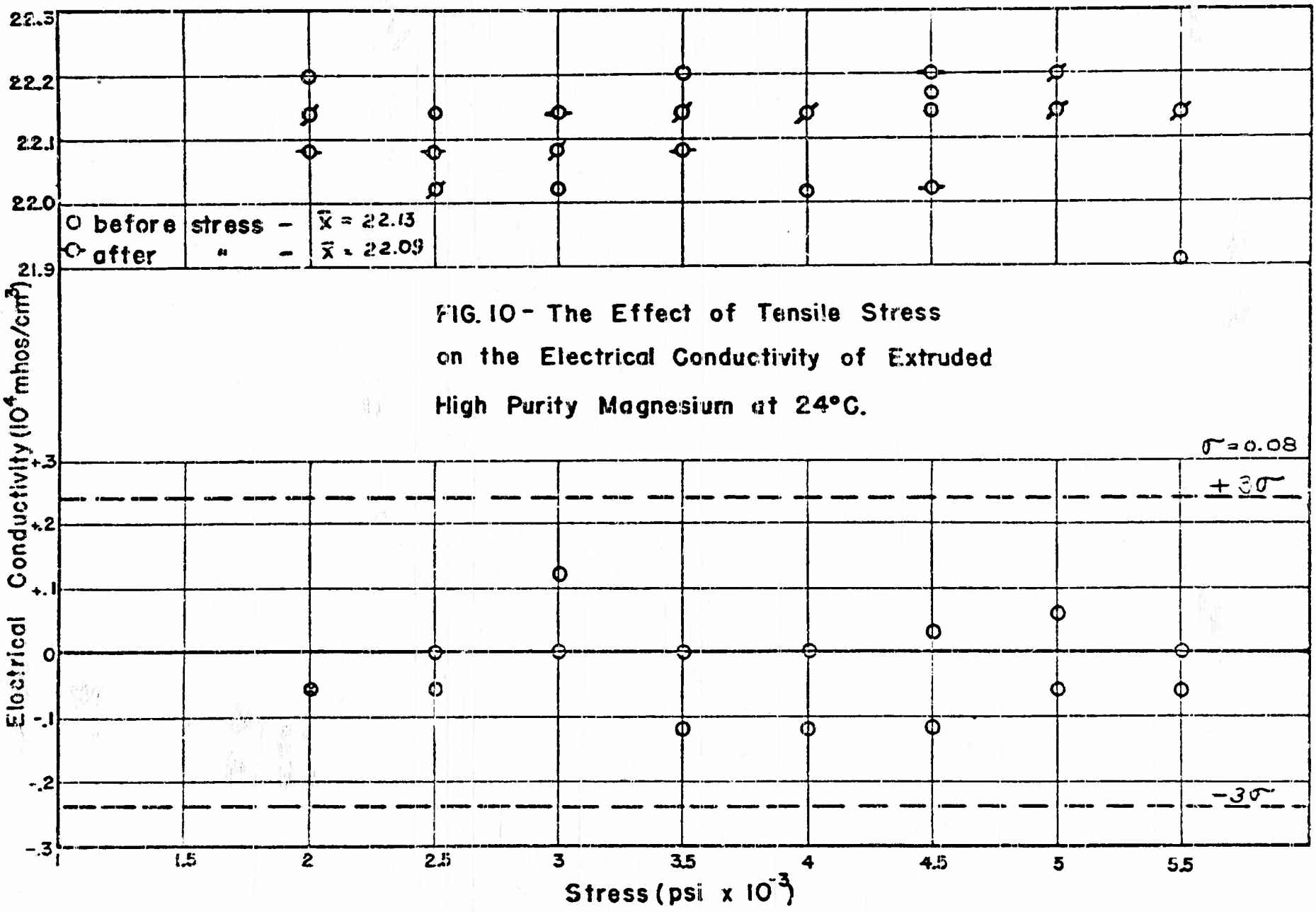


FIG. 10 - The Effect of Tensile Stress on the Electrical Conductivity of Extruded High Purity Magnesium at 24°C.

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